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# Exact Amplitude–Based Resummation QCD Predictions and LHC Data

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## Abstract

We present the current status of the comparisons with the respective data of the predictions of our approach of exact amplitude-based resummation in quantum field theory as applied to precision QCD calculations as needed for LHC physics, using the MC Herwiri1.031. The agreement between the theoretical predictions and the data exhibited continues to be encouraging.

**Keywords:** QCD Resummation IR-Improved DGLAP-CS Theory NLO-PS MC

## 1. Introduction

Large samples of data on SM standard candle processes such as heavy gauge boson production and decay to lepton pairs (samples exceeding  $10^7$  events for  $Z/\gamma^*$  production and decay to  $\ell\bar{\ell}$ ,  $\ell = e, \mu$ ) now exist for ATLAS and CMS as a result of the successful running of the LHC during 2010–2012. Such data signal the arrival of the era of precision QCD, wherein one needs predictions for QCD processes at the total precision tag of 1% or better, and make more manifest the need for exact, amplitude-based resummation of large higher order effects. Indeed, with such resummation one may have better than 1% precision as a realistic goal as we have argued in Refs. [1]. With such precision one may distinguish new physics(NP) from higher order SM processes and may distinguish different models of new physics from one another as well. Here, we present the status of this application of exact amplitude-based resummation theory in quantum field theory in relation to recent available data from the LHC.

Our discussion proceeds as follows. We review the elements our approach to precision LHC physics, an amplitude-based QED $\otimes$ QCD( $\equiv$  QCD  $\otimes$  QED) exact resummation theory [2] realized by MC methods. This review is followed in the next section by the comparisons

with recent LHC data with an eye toward precision issues.

We start from the well-known fully differential representation

$$d\sigma = \sum_{i,j} \int dx_1 dx_2 F_i(x_1) F_j(x_2) d\hat{\sigma}_{\text{res}}(x_1 x_2 s) \quad (1)$$

of a hard LHC scattering process, where  $\{F_j\}$  and  $d\hat{\sigma}_{\text{res}}$  are the respective parton densities and reduced hard differential cross section and we indicate that the latter has been resummed for all large EW and QCD higher order corrections in a manner consistent with achieving a total precision tag of 1% or better for the total theoretical precision of (1). The total theoretical precision  $\Delta\sigma_{\text{th}}$  of (1) can be decomposed into its physical and technical components as defined in Refs. [3, 4] and its value is essential to the faithful application of any theoretical prediction to precision experimental data for new physics signals, SM backgrounds, and over-all normalization considerations. Whenever  $\Delta\sigma_{\text{th}} \leq f \Delta\sigma_{\text{expt}}$ , where  $\Delta\sigma_{\text{expt}}$  is the respective experimental error and  $f \lesssim \frac{1}{2}$ , the theoretical uncertainty will not adversely affect the analysis of the data for physics studies. With the goal of achieving a provable theoretical precision tag we have developed the QCD  $\otimes$  QED resummation theory in Refs. [2] for all components of (1). The exact master formula

from which we start is

$$d\hat{\sigma}_{\text{res}} = e^{\text{SUM}_{\text{IR}}(\text{QCD})} \sum_{n,m=0}^{\infty} \frac{1}{n!m!} \int \prod_{j_1=1}^n \frac{d^3 k_{j_1}}{k_{j_1}} \prod_{j_2=1}^m \frac{d^3 k'_{j_2}}{k'_{j_2}} \int \frac{d^4 y}{(2\pi)^4} e^{i y \cdot (p_1 + q_1 - p_2 - q_2 - \sum k_{j_1} - \sum k'_{j_2}) + D_{\text{QCD}}} \tilde{\beta}_{n,m}(k_1, \dots, k_n; k'_1, \dots, k'_m) \frac{d^3 p_2}{p_2^0} \frac{d^3 q_2}{q_2^0}. \quad (2)$$

Here  $d\hat{\sigma}_{\text{res}}$  is either the reduced cross section  $d\hat{\sigma}_{\text{res}}$  or the differential rate associated to a DGLAP-CS [5, 6] kernel involved in the evolution of the  $\{F_j\}$  and the new (YFS-style [7, 8]) non-Abelian residuals  $\tilde{\beta}_{n,m}(k_1, \dots, k_n; k'_1, \dots, k'_m)$  have  $n$  hard gluons and  $m$  hard photons and we show the generic  $2f$  final state with momenta  $p_2, q_2$  for definiteness. The infrared functions  $\text{SUM}_{\text{IR}}(\text{QCD}), D_{\text{QCD}}$  are given in Refs. [2, 9, 10]. The residuals  $\tilde{\beta}_{n,m}$  allow a rigorous parton shower/ME matching via their shower-subtracted counterparts  $\hat{\beta}_{n,m}$  [2].

We now discuss the paradigm opened by (2) for precision QCD in the context of comparisons with recent data.

## 2. Precision QCD for the LHC: Comparison to Data

We first recall that, as we have discussed in Refs. [1], the methods we employ for resummation of the QCD theory are fully consistent with the methods in Refs. [11, 12, 13, 14, 15, 16] but we do not have intrinsic physical barriers to sub-1precision as do the approaches used in the latter references. They may be used to give approximations to our new residuals  $\tilde{\beta}_{m,n}$  for qualitative studies of consistency, for example. Such matters will be addressed elsewhere [17].

With this understanding, we note that, if we apply (2) to the calculation of the kernels,  $P_{AB}$ , we arrive at an improved IR limit of these kernels, IR-improved DGLAP-CS theory. In this latter theory [9, 10] large IR effects are resummed for the kernels themselves. From the resulting new resummed kernels,  $P_{AB}^{\text{exp}}$  [9, 10] we get a new resummed scheme for the PDF's and the reduced cross section:

$$F_j, \hat{\sigma} \rightarrow F'_j, \hat{\sigma}' \text{ for}$$

$$P_{gq}(z) \rightarrow P_{gq}^{\text{exp}}(z) = C_F F_{YFS}(\gamma_q) e^{\frac{1}{2}\delta_q} \frac{1 + (1-z)^2}{z} z^{\gamma_q}, \text{ etc.}$$

As discussed in Ref. [1], this new scheme gives the same value for  $\sigma$  in (1) with improved MC stability. Here,  $C_F$  is the quadratic Casimir invariant for the quark color representation and the YFS [7] infrared factor is given

by  $F_{YFS}(a) = e^{-C_E a} / \Gamma(1+a)$  where  $C_E$  is Euler's constant. We refer the reader to Ref. [9, 10] for the definition of  $\gamma_q, \delta_q$  as well as for the complete set of results for the new  $P_{AB}^{\text{exp}}$ .

The basic physical idea underlying the new kernels was already shown by Bloch and Nordsieck [18]: due to the coherent state of very soft massless quanta of the attendant gauge field generated by an accelerated charge it is impossible to know which of the infinity of possible states one has made in the splitting process  $q(1) \rightarrow q(1-z) + G \otimes G_1 \cdots \otimes G_\ell, \ell = 0, \dots, \infty$ . The new kernels take this effect into account by resumming the terms  $O((\alpha_s \ln(q^2/\Lambda^2) \ln(1-z))^n)$  for the IR limit  $z \rightarrow 1$ . This resummation generates [1, 9, 10] the Gribov-Lipatov exponents  $\gamma_A$  which therefore start in  $O(\hbar)$  in the loop expansion<sup>1</sup>.

The first realization of the new IR-improved kernels is given by new MC Herwiri1.031 [1] in the Herwig6.5 [20] environment. Realization of the new kernels in the Herwig++ [21], Pythia8 [22], Sherpa [23] and Powheg [24] environments is in progress as well. In Fig. 1 we illustrate some of the recent comparisons we have made between Herwiri1.031 and Herwig6.510, both with and without the MC@NLO [25] exact  $O(\alpha_s)$  correction<sup>2</sup>, in relation to the LHC data [26, 27] on  $Z/\gamma^*$  production with decay to lepton pairs<sup>3</sup>. Just as we found in Refs. [1] for the FNAL data on single  $Z/\gamma^*$  production, the unimproved MC requires the very hard value of  $\text{PTRMS} \cong 2.2\text{GeV}$  to give a good fit to the  $p_T$  spectra as well as the rapidity spectra whereas the IR-improved calculation gives very good fits to both of the spectra without the need of such a hard value of  $\text{PTRMS}$ , the rms value for an intrinsic Gaussian  $p_T$  distribution, for the proton wave function: the  $\chi^2/d.o.f$  are respectively (0.72, 0.72), (1.37, 0.70), (2.23, 0.70) for the  $p_T$  and rapidity data for the MC@NLO/HERWIRI1.031, MC@NLO/HERWIG6.510( $\text{PTRMS} = 2.2\text{GeV}$ ) and MC@NLO/HERWIG6.510( $\text{PTRMS} = 0$ ) results. Such an ad hoc hard intrinsic value of  $\text{PTRMS}$  contradicts the results in Refs. [30, 31], as we discuss in Refs. [1]. To illustrate the size of the exact  $O(\alpha_s)$  correction, we also show the results for both Herwig6.510 (green line) and Herwiri1.031 (blue line) without it in the plots in Fig. 1. As expected, the exact  $O(\alpha_s)$  correction is impor-

<sup>1</sup>See Ref. [19] for the connection between the new kernels and the Wilson expansion.

<sup>2</sup>See Refs. [1] for the connection between the  $\hat{\beta}_{n,m}$  and the MC@NLO differential cross sections.

<sup>3</sup>Similar comparisons were made in relation to such data [28, 29] from FNAL in Refs. [1].

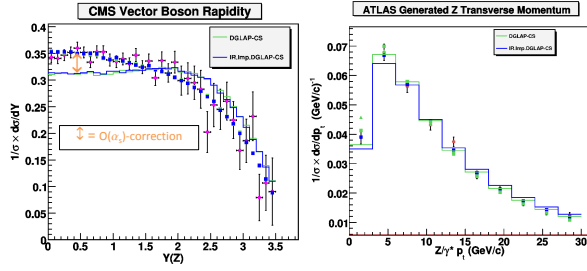


Figure 1: Comparison with LHC data: (a), CMS rapidity data on  $(Z/\gamma^*)$  production to  $e^+e^-$ ,  $\mu^+\mu^-$  pairs, the circular dots are the data, the green(blue) lines are HERWIG6.510(HERWIRI1.031); (b), ATLAS  $p_T$  spectrum data on  $(Z/\gamma^*)$  production to (bare)  $e^+e^-$  pairs, the circular dots are the data, the blue(green) lines are HERWIRI1.031(HERWIG6.510). In both (a) and (b) the blue(green) squares are MC@NLO/HERWIRI1.031(HERWIG6.510(PTRMS = 2.2 GeV)). In (b), the green triangles are MC@NLO/HERWIG6.510(PTRMS = 0). These are otherwise untuned theoretical results.

tant for both the  $p_T$  spectra and the rapidity spectra. The suggested accuracy at the 10% level shows the need for the NNLO extension of MC@NLO, in view of our goals for this process. We also note that, with the 1% precision goal, one needs per mille level control of the EW corrections. This issue is addressed in the new version of the  $\mathcal{K}\mathcal{K}$  MC [32], version 4.22, which now allows for incoming quark antiquark beams – see Ref. [32] for further discussion of the relevant effects in relation to other approaches [33].

We have also made comparisons with recent LHCb data [34] on single  $Z/\gamma^*$  production and decay to lepton pairs. These results will be presented in detail elsewhere [17]. Here, we illustrate them with the results in Fig. 2 for the  $Z/\gamma^*$  rapidity as measured by LHCb for the decays to  $e^+e^-$  pairs and the decays to  $\mu^+\mu^-$  pairs. These data probe a different phase space regime as the acceptance on the leptons satisfies the pseudorapidity  $\eta$  constraint  $2.0 < \eta < 4.5$  to be compared with the acceptance of  $|\eta_\ell| < 2.1$  ( $|\eta_\ell| < 2.4$ ),  $|\eta_{\ell'}| < 4.6$  ( $|\eta_{\ell'}| < 2.4$ ) for the CMS(ATLAS) data in Fig. 1. Here  $\eta_\ell(\eta_{\ell'})$  is the respective pseudorapidity of  $\ell$ ,  $\ell = \mu, \bar{\mu}(\ell', \ell' = e, \bar{e})$ , respectively. Again, the agreement between the IR-improved MC@NLO/Herewir1.031 without the need of a hard value of PTRMS is shown for both the  $e\bar{e}$  and  $\mu\bar{\mu}$  data, where the  $\chi^2/d.o.f.$  are 0.746, 0.773 respectively. The unimproved calculations with MC@NLO/Herwig6510 for PTRMS = 0 and PTRMS = 2.2 GeV respectively also give good fits here, with the  $\chi^2/d.o.f.$  of 0.814, 0.836 and 0.555, 0.537 respectively for the  $e\bar{e}$  and  $\mu\bar{\mu}$  data. Thus, in the phase space probed by the LHCb, it continues to hold that the more inclusive ob-

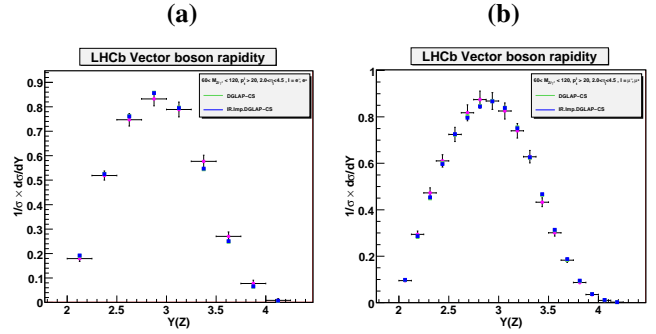


Figure 2: Comparison with LHC data: LHCb rapidity data on  $(Z/\gamma^*)$  production to (a)  $e^+e^-$ , (b)  $\mu^+\mu^-$  pairs, the circular dots are the data. In both (a) and (b) the blue(green) squares are MC@NLO/HERWIRI1.031(HERWIG6.510(PTRMS = 2.2 GeV)) and the green triangles are MC@NLO/HERWIG6.510(PTRMS = 0). These are otherwise untuned theoretical results.

servables such as the normalized  $Z/\gamma^*$  rapidity spectrum are not as sensitive to the IR-improvement as observables such as the  $Z/\gamma^*$   $p_T$  spectrum.

As one has now more than  $10^7$   $Z/\gamma^*$  decays to lepton pairs per experiment at ATLAS and CMS, we show in Refs. [1] that one may use the new precision data to distinguish between the fundamental description in Herwig1.031 and the ad hocly hard intrinsic  $p_T$  in Herwig6.5 by comparing the data to the predictions of the detailed line shape and of the more finely binned  $p_T$  spectra – see Figs. 3 and 4 in the last two papers in Refs. [1]<sup>4</sup>. We await the availability of the new precision data accordingly.

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<sup>4</sup>The discriminating power among the attendant theoretical predictions of  $p_T$  spectra in single  $Z/\gamma^*$  production at the LHC is manifest in Refs. [35] – the last paper in Refs. [1] provides more discussion on this point.

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